Design of Permanent Magnet Bearings with high stiffness

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I. Introduction

The stiffness of permanent magnet bearings, PMB's, composed of only two magnet rings is limited, and it is well known that increasing the size of these magnets by increasing their cross section area has a very limited effect on bearing performance. Instead, in order to gain enough stiffness, axially stacked structures of comparatively smaller permanent magnets are frequently being used, Fig. 1a. By arranging the magnets with alternating polarity, the flux derivatives as well as the bearing stiffness are known to be increased.

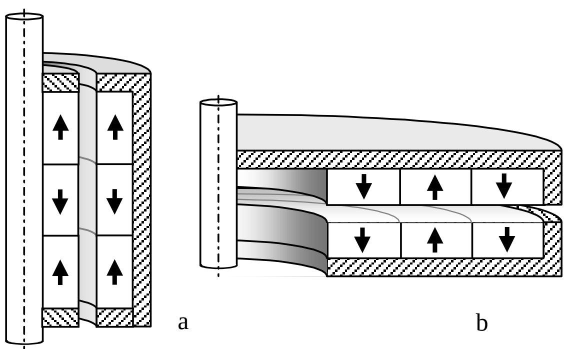

Fig. 1a) Axially stacked structure and b) concentrically stacked structure of permanent magnet bearings

Fremerey [1] later achieved the same effect by stacking the magnets concentrically, Fig. 1b. The latter arrangement has the advantage that it will reduce the axial length of the bearing, and it will also allow the magnets to operate in attractive mode, thus avoiding the risk of demagnetization.

Yonnet [2] proposed a special type of stacked structures for the axial stack: a so called rotating magnetization direction system (RMD). Such a stack could be realized as illustrated in Fig. 2a. This could also be applied to Fremereys design which could be described as a concentrically oriented Halbach array Fig. 2b.

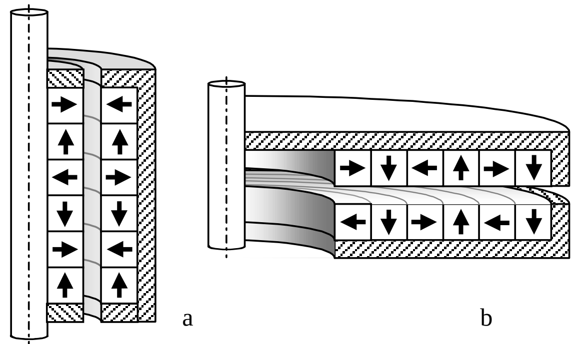

Fig. 2a) Axially and b) concentrically stacked PM-Bearings with Halbach structures or also called rotating magnetization direction (RMD) structures.

The system consists of several magnet rings with alternate axial and radial magnetization directions. An increased stiffness by factor 1.8 compared to conventional stack structures is reported. We can confirm this value by our own calculations.

In this paper we will step by step show how the magnet structure can be further improved. It will result in an arrangement, Fig. 8, which has 45% higher radial stiffness than Yonnets proposal, Fig. 2a.

1. The first step is to verify the analytical results from Yonnet using modern FEM codes, Section II.

2. The second step is to optimise the pole width. From former investigations it is known that the pole width has a certain relation to the gap. [3, 4]. This is done in Sections III and IV.

3. Finally in Section V we apply a more continuous change of magnetization direction by minimizing the magnet size and adjusting the magnetization angle so that optimum pole width is achieved. (In [2] an increment of 90° was used, we are using e.g. 27°).

II. Stiffness of Basic Configuration

As a starting point we calculated the radial stiffness of an axially stacked structure (see Fig. 1a) and compared it with the axially stacked RMD structure, see Fig. 2a. Both arrangements have the same properties: They operate in repellent mode. They are radially stable and, axially unstable. Therefore these arrangements are used as radial bearings. But, within the same dimensions the RMD structure (Fig. 2a) achieves a higher radial stiffness.

Fig. 3 shows the computed magnet fields of the axially stacked structure and Fig. 4 the RMD structure. The magnetization vector changes its direction by 180° from magnet to magnet in the axially stacked structure (Fig. 3) and by 90° in the RMD system (Fig. 4).

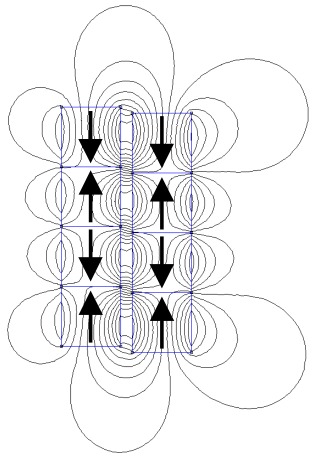

Fig. 3 Radial bearing with axially stacked structure of permanent magnets.

The radial stiffness in Fig. 3 is s_r = 226 N/mm while in Fig. 4 we get s_r = 418 N/mm, which is a factor 1.8 greater than previous configuration. Fig. 4 represents the proposal from [2].

For the calculation we used FEMM [5], a finite element program for calculating two dimensional (2D) and axisymmetric (RS) magnet fields. We calculated the force in initial position and in axially displaced position of 0.5 mm. The axial stiffness s_{ax} was calculated from the force difference. The radial stiffness s_r is simply obtained by Earnshaw’s Theorem:

$$s_r = -\frac{1}{2} \cdot s_{ax} . \quad (1)$$

This is possible by the relative permeability of magnets µ = 1.048, which is close to 1 and the absence of any high permeable material like steel. Otherwise a 3D program has to be used. The dimensions of the bearing are shown in Table 1, magnetization M= 950 kA/m and relative permeability µ=1.048. The overall height of the structure is always 20 mm.

TABLE I
Dimension of magnet rings in Fig. 3 and Fig.4

	Inner Radius	Outer Radius	Height Fig. 3	Height Fig. 4
Inner ring	20mm	25 mm	5 mm	2.5 mm
Outer ring	26mm	31 mm	5 mm	2.5 mm

The calculations performed here are valid for the axial stack, but in principle the optimization procedure can be directly adopted for the concentric stack (Fig2b) as well.

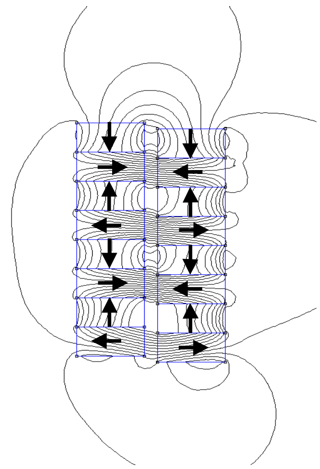

Fig. 4 Radial bearing with axially stacked rotating magnetization direction (RMD) structure of permanent magnets.

III. Applying Optimum Pole Width on the Axially Stacked Structures

Former investigations [3, 4] showed that the cross section should have a certain relation to the gap for obtaining maximum stiffness. For example, the stiffness-to-volume ratio (specific stiffness) of a concentrically stacked structure (Fig. 1b) is maximum if the magnet height and the pole width of one magnet are close to or slightly greater than the gap width. For the axially stacked system in Fig 3 we searched for an optimum pole width. Keeping the outer dimensions constant but varying the numbers of rings, the best solution (Fig. 5) can be obtained with 6 magnet rings and a magnet height of 3.3 mm instead of 4 magnet rings with a height of 5 mm.

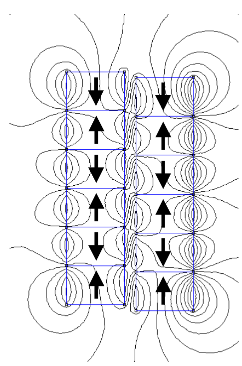

Fig. 5 Axially stacked structure with optimized pole width:6 magnet rings, radial stiffness: 265 N/mm

The radial stiffness of the structure in Fig 5 is s_r = 265 N/mm, which is 17% better than the basic configuration in Fig. 1a but obviously less than the RMD proposal shown in Fig. 1b.

An interesting side-effect is the following: It is possible to build the basic configuration with 50% of the magnet volume and the same radial stiffness as in Fig. 3. In Fig. 6 the arrangement for a space saving solution is shown. It consists of a stack of 8 magnets with a square cross section of 2.5 mm. The overall height of the structure is again 20 mm.

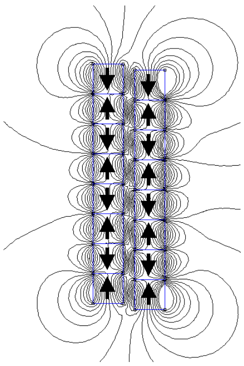

Fig. 6 Space - saving solution of axially stacked structures with radial stiffness s_r = 226 N/mm

IV Applying optimum pole width on RMD systems

Applying the optimum pole width rule to the RMD configuration, we get the best solution with a magnet height of 1.5 mm. The optimized arrangement shown in Fig. 7 has a radial stiffness of s_r = 511 N/mm, which is 22% more than the radial stiffness of the RMD-configuration in Fig. 4. Note that the upper and the lowest magnet have a height of 1 mm only to meet the total height of 20 mm of the stack.

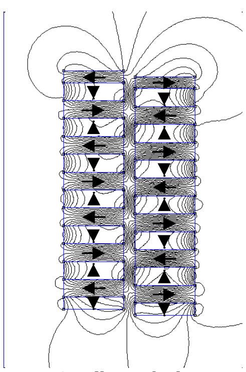

Fig. 7 Axially stacked rotating magnetization direction (RMD) structure with optimized pole width, radial stiffness s_r = 511 N/mm.

V Applying thinner steps of changing the magnetization direction on the RMD system

The arrangement in Fig. 8 has an almost continuous magnetization change. It consists of 40 magnet slices each 0.5 mm thick. The magnetization direction changes from slice to slice of 29°. This angle gives the best results among different calculations. We get a radial stiffness of sr = 613 N/mm. This is 46% better than Yonnet's proposal [2] and 20% better than the stack with optimized pole width in Fig. 7. With more thinner magnet slices the stiffness would further increase and approach an asymptotic upper limit. It seems that the presented solution is not far from the theoretical maximum.

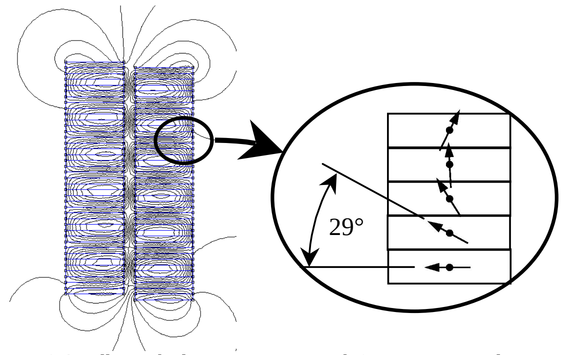

Fig. 8 Axially stacked RMD structure with 0.5 mm magnet slices and optimized pole width, radial stiffness s_r = 613 N/mm.

VI Discussion

Fig. 9 shows a comparison of all presented magnet structures. The highest stiffness can be obtained with continuous magnetization and an appropriate pole width.

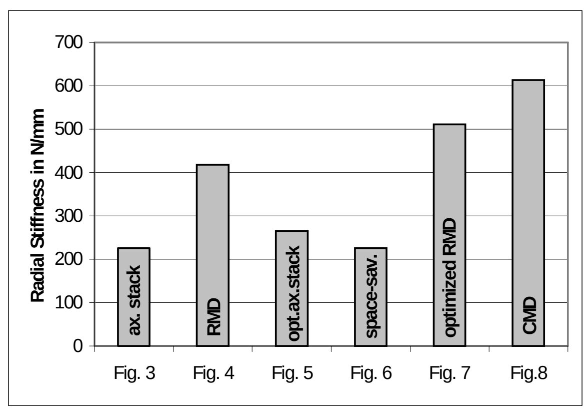

Fig. 9 Comparison of the radial stiffness of all investigated magnet structures.

There are unresolved questions, concerning the practical realization of such magnet arrangements. Especially the magnetization and the assembly of thin magnet slices will be a challenge. One solution could be the use of an isotropic magnet material and the continuous magnetization in only one single magnet bulk.

VII SUMMARY

This paper shows the tendency for an improved design. Design goal is maximum stiffness within a constant volume and only one vertical air gap. Concerning high stiffness values we can confirm the advantage of RMD-structures if compared to axially magnetized stacks only.

Optimized pole width yields a further increased stiffness of almost 20% in the calculated examples.

With applying of continuous magnetization direction change a further increased stiffness becomes possible. The almost continuous magnetization in Fig. 8 shows a better solution of 20 % if compared to the optimized RMD structure with an increment of magnetization direction change of 90°.

Similar investigation can also be done for maximum force.

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